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Evaluation of two microwave surface distribution systems designed for substratum and agricultural soil disinfection

B. Velázquez-Martí* and C. Gracia-López
Departamento de Mecanización y Tecnología Agraria. Universidad Politécnica de Valencia. C/ Camino de Vera, 14. 46022 Valencia. Spain

Abstract

Heat treatment by microwave for soil disinfection may represent an alternative to chemical treatments. One of the main problems in the design of microwave applicators for agricultural soil disinfection is to achieve a homogeneous surface energy distribution. This work has been carried out in order to evaluate two systems which can solve this problem: the first one is based on the use of a slotted waveguide and the other is based on overlapping the radiation of several magnetrons working simultaneously. Initially, the systems were modelled using an algorithm based on Maxwell equations in order to give a first overview of the system functioning. In a second step, the models were validated by comparison with thermal maps obtained empirically. As a consequence of this work we propose a re-design of the slotted waveguide system to improve the homogeneity of the temperature distribution over a large radiation area. The overlapping system gave adequate homogeneity for commercial purposes.
Key words: weed control, waveguide, soil radiation, overlapping radiation.

Resumen

Evaluación de dos sistemas de distribución superficial de microondas diseñados para la desinfección de sustratos y suelos agrícolas

El tratamiento térmico con microondas para la desinfección de suelos representa una alternativa a los tratamientos químicos. Uno de los principales problemas en el diseño de aplicadores de microondas para la desinfección de suelos y sustratos agrícolas es conseguir una distribución superficial homogénea en la transformación de energía. En este trabajo se presenta la evaluación de dos sistemas para solucionar este problema: un sistema basado en el empleo de un guía de ondas ranurado y otro sistema basado en solapar la radiación de varios magnetrones actuando simultáneamente. Inicialmente los sistemas fueros modelados usando un algoritmo basado en las ecuaciones de Maxwell para dar una primera idea de su funcionamiento. Como segundo paso los modelos fueron validados mediante comparación con mapas de temperatura obtenidos de forma empírica. Como consecuencia de este estudio se propone un nuevo diseño del sistema de guía de ondas para mejorar la homogeneidad de la distribución de temperatura en una área de radiación amplia. El sistema de solapamiento de la radiación dio una adecuada homogeneidad para aplicaciones comerciales.
Palabras clave: control de malas hierbas, guía de ondas, radiación del suelo, solapamiento de la radiación.

Introduction

Microwave radiation is an alternative to herbicides and fungicides in soils to eliminate weeds and pathogenic microorganisms because this method does not produce chemical residues after the applications (Olsen and Hammer, 1982; Nelson, 1985; Mavrogianopoulos *et al.*, 2000). This physical method of disinfection is based on increasing the temperature of a soil and the pathogens inside it, by radiating with high frequency electromagnetic waves (1-1,000 GHz) (Nelson, 1996). Elimination of pathogens is achieved when a specific threshold temperature is maintained for a sufficient time. This threshold is usually called *death thermal points.* At this temperature, proteins are denaturised becoming inactive and leading to the death of pathogenic organisms (Fujiwara *et al.*, 1983; Disprose *et al.*, 1984; Barker and Craker, 1991; Catalá-Civera and de los Reyes, 1999a, 1999b).

The principle of microwave heating is based on tuning the frequency with the oscillation resonance

* Corresponding author: borvemar@dmta.upv.es
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Authors are members of SEA.

range of molecules such as water. This leads to a strong molecular shaking (resonant critical speed) and, as a consequence, to the generation of heat inside the material (Metaxas and Meredith, 1983). When microwaves are applied to soils, wave propagation suffers an important attenuation with depth (Velázquez-Martí *et al.*, 2003b), thereby limiting the use of applicators to automatic sowing lines for greenhouses (horticultural nurseries), where plants are sown into trays with narrow layers of soil or substratum (Gracia-López and Velázquez-Martí, 2002).

One of the main objectives in the design of microwave applicators is to achieve a homogeneous surface distribution of the energy, leading to a uniform heating effect (Cebrian-Gascón *et al.*, 1999). Presently, commercial applicators are using the *mode shakers* that produce changes in the distribution and direction inside the oven and a mechanical revolving movement of the irradiated material (Cebrian-Gascón *et al.*, 1999). However, these solutions are not adequate for soil applications due to the static state of soils and the large area involved in disinfection treatments (Velázquez-Martí *et al.,* 2003a). In this work, two methods that may allow a uniform spatial distribution of the radiation in a surface layer have been studied. These radiation distribution systems are based on: a) the use of a slotted waveguide, b) the use of several magnetrons in line emitting simultaneously.

The objective of this study was to investigate to what extent these two types of microwave applicators were able to distribute the radiation uniformly for substratum and agricultural soil disinfection.

Material and Methods

System based on slotted waveguide

According to values of dielectric properties obtained for different agricultural soils (Velázquez-Martí *et al.,* 2003b), a waveguide was designed to achieve a uniform radiation distribution over a large ground area. The waveguide consisted in a hollow pipe of a conductor material capable of guiding the electromagnetic energy in a previously determined direction. Propagation was achieved by multiple reflections inside the waveguide walls (Krauss and Fleisch, 1999). Being slotted, the waveguide irradiated a relatively large surface, more or less uniformly (Cebrian-Gascón *et al.*, 1999).

By testing several sizes, the waveguide dimensions were designed to minimize the reflection of the emitter system in the ISM (industrial, scientific and medical applications) bands, specifically between 915 and 2450 MHz. The waveguide designed was a rectangular hollow pipe, with a section of 8.6×4.4 cm, and 85 cm long. It had 6 slots on the lower side, parallel to the soil. The slots were tilted 45º to the longitudinal axis, and were 10 cm apart (Fig. 1). The waveguide was fed with a 4 kW magnetron placed at its end.

Subsequently, field performance and return loss of the emitter system were evaluated using a *Vector Network Analyser*. The antenna radiation diagram was obtained in an *anechoic chamber,* which shows field intensity of emitted power in a transversal plane of the guide, using polar coordinates ϕ and r. The anechoic chamber is a room in which the walls do not reflect electromagnetic waves. A detector revolving around the applicator in its transversal plane measures the intensity of irradiated waves associated to each coordinate, which are recorded in a datalogger.

Once the antenna diagram was obtained, the characteristics of the waveguide radiation field were simulated using the MAFIA (Maxwell Finite Integration Algorithm), in order to obtain the heating energy density over a soil surface of 80×20 cm, placed

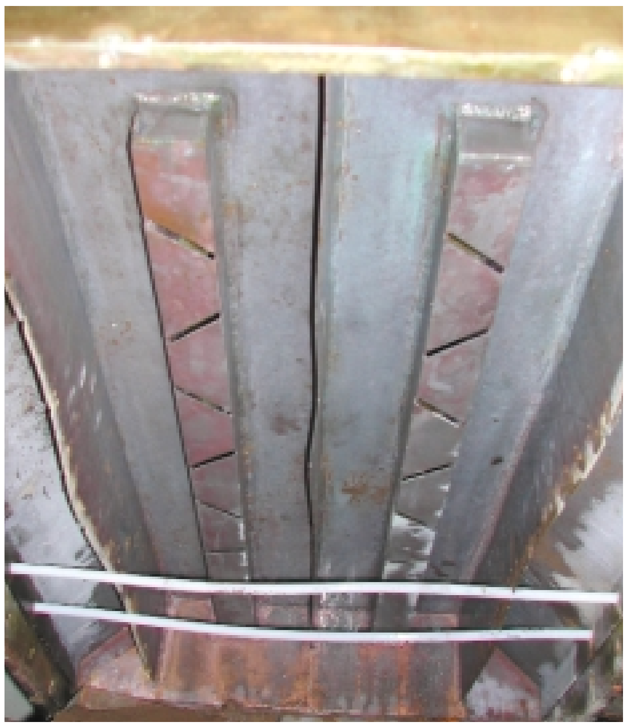

Figure 1. Slotted waveguide.

10 cm under the guide. MAFIA is a consistent formulation for the discrete representation of Maxwell's equations on numeric grids (Weiland, 1977; van Rienen and Weiland, 1985). The matrix equations for the electromagnetic energy quantities are obtained by finite integration techniques of Maxwell's equations with respect to charge and energy conservation. The algorithm ensures an especially favourable stability and convergence behaviour. Another decisive advantage of this formulation in comparison with other methods is that it represents a comprehensive theory which can be successfully used within the whole spectrum of electromagnetic applications.

System based on several magnetrons emitting simultaneously

Simulation runs with MAFIA were carried out to compare the heating density of the previous system with one given by an emitter head with a magnetron of 1 kW placed vertically through a waveguide without slots, open at its end and situated in the middle of the irradiated surface. In this case, the heating density was obtained for a surface of 80 × 20 cm placed 20 cm under the guide. This longer distance from the surface to the emitter, allows irradiation of a larger surface compared to the previous prototype (Fig. 2).

After analysing the outputs of simulation runs, it was decided to design a system based on radiation overlapping of four 1 kW magnetrons, separated 35 cm apart. The energy density was estimated from a new set of MAFIA simulations, for a surface of 150 × 50 cm, located 20 cm from the emitters (Fig. 3). This simulation is depicted in Figure 12. Outputs of the

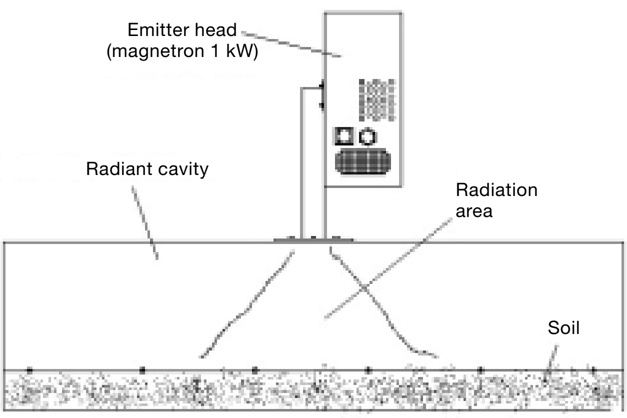

Figure 2. Vertical head emitter.

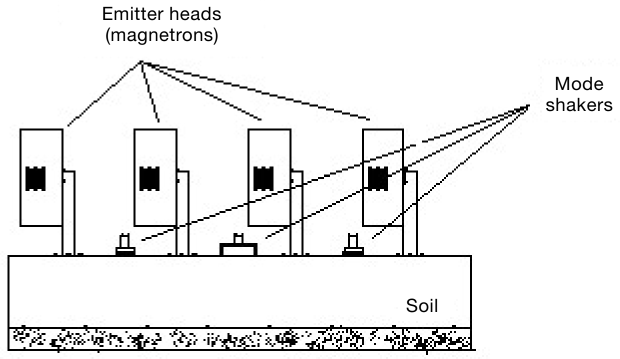

Figure 3. Emitter head in line capable of overlapping its radiation surface.

simulations were contrasted with temperature measurements.

Temperature measurements in the evaluation of the slotted waveguide prototype

For evaluating the waveguide system, the prototype was placed longitudinally over a metallic container of octagonal section of 100 cm long, 58 cm wide and 38 cm high, with a storage capacity of 200 kg of soil. The applicator was fed by a 4 kW radiofrequency power through a water-cooled magnetron. The waveguide was situated in a lateral band position (Fig. 4), at 8 cm from the soil surface. This asymmetric position allowed the energy absorbed by the soil column located under the waveguide and the energy deflected to the lateral soil columns to be evaluated.

The metallic prism that forms the oven was perforated with 36 circular holes of 3 cm^2 on each side, forming a matrix of 6 rows 5 cm apart and 6 columns 10 cm apart. The holes gave direct access inside the oven, and allowed soil samples to be collected and to soil humidity to be measured in each experiment without opening the oven lid. Thermocouples were inserted at 72 positions within the irradiated soil

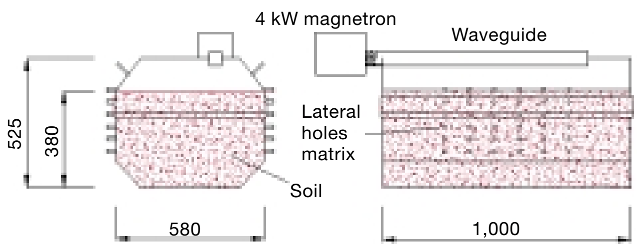

Figure 4. Schematic views of the waveguide applicator (sizes are in mm).

Figure 5. A: Full oven view of soil with its lid open before radiation. B: Thermocouples placed in a holed column in the side matrix of the container.

volume to measure the temperature distribution. Half of them (36) were placed in a vertical-longitudinal plane under the slotted-waveguide, and the other 36 were placed on a parallel level 20 cm away from the previous plane. The thermocouples were distributed by columns 10 cm apart, starting below the first feeding slot. Groups of 12 were placed at the soil surface, at 5, 10, 15, 20 and 25 cm of depth (Fig. 5). The soil was irradiated with different exposure times (0, 120, 180, 240, 300, 360, 420, 480, 540 and 600 s). Fifteen repetitions were made for each exposure time. The temperature of the probes was recorded every 20 s. These measurements allowed the thermal map to be obtained for different depths during heating and cooling. The soil energy distribution was calculated by dividing the soil into 12 rectangular sectors of 10×20 cm^2, using the temperatures and the estimated soil specific heat as parameters.

Temperature measurements in the system evaluation based in several magnetrons

Due to the strong temperature attenuation within the first centimetres of soil depth, the evaluation of the second prototype was carried out using trays of 6 cm depth.

The applicator prototype is formed by a rectangular multimode cavity of $150 \times 50 \times 30$ cm, with four microwave emitter heads of 1 kW each. The heads were fixed on the upper wall cavity, arranged vertically and 35 cm apart. Three mode shakers were placed between each emitter head. The mode shakers vary the particular conditions of the Maxwell differential equations rapidly changing the electromagnetic field distribution. This fast distribution variation is desired to produce a better heat uniformity.

The trays filled with the substratum to be treated were $50 \times 40 \times 6$ cm. In each treatment, the tray was inserted in and withdrawn from the mode cavity through two gates 42 cm wide $\times$ 6.5 cm high. Each gate was protected with microwave filters, which allowed a continuous functioning of the system (Fig. 6). The time of exposure varied in each experiment (0, 120, 180, 240, 300, 360 and 480 s) and the temperature measurements were taken before the start and after the end of the treatment. Measurements were taken at three locations on the tray: at the centre, and at two other points 12.5 cm from the centre during heating and cooling.

The heat distribution obtained from the temperature measurements with the prototype was calculated for 12 rectangular sectors of 20×25 cm^2.

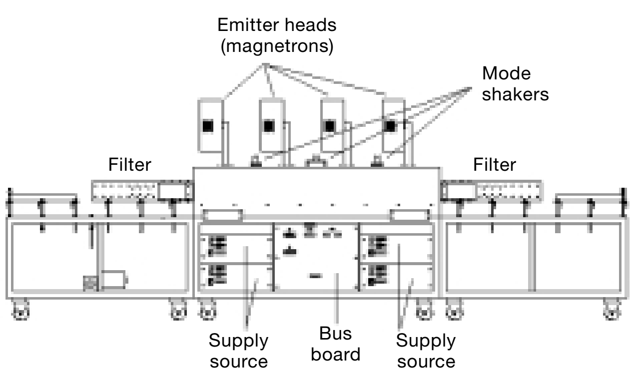

Figure 6. Modular microwave oven.

In both tests, the temperature probes were Cromel-Alumel thermocouples with mineral insulation of magnesium oxide and Inconel sheathing 250 mm long. These sensors are especially designed for measurements in microwave fields.

Results

Radiation and temperature generated by the waveguide system

Prior to the evaluation, the waveguide was tested with the Vector Network Analyser, showing a maximum transmission at 2,450 MHz.

Figure 7 depicts the antenna radiation diagram that shows the field intensity of the emitted power in a transversal plane of the guide, using polar coordinates and r. With the designed waveguide we obtained the maximum energy lobe at 9º. This direction is practically perpendicular to the soil surface. There are also secondary lobes at 45º, 280º and 315º. These secondary lobes have a lower intensity but allow a wider area to be irradiated. No energy was detected in the directions between 90º and 270º due to the specific design of the waveguide.

Simulation of the thermal distribution at the soil surface, irradiated with the slotted waveguide, is shown in Figure 8. The maximum temperatures are reached in the area near to the waveguide end, where the microwave power source is situated. The areas furthest away from the source are poorly and unevenly heated.

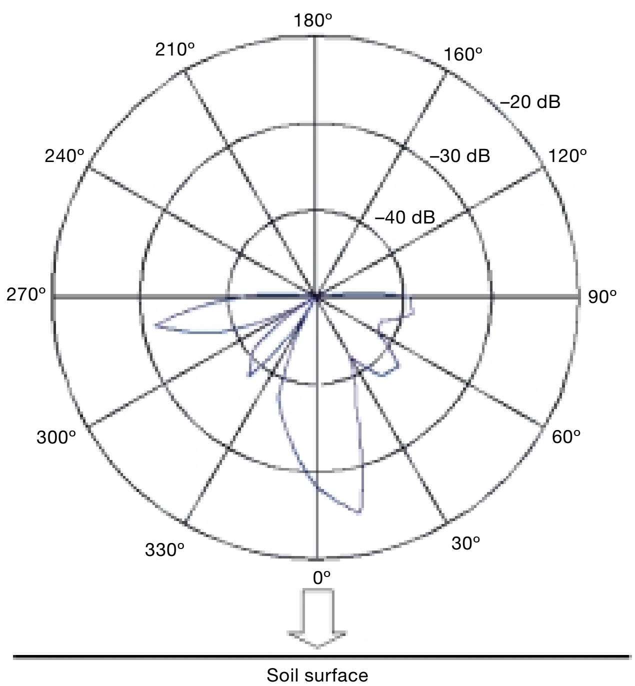

Figure 7. Slotted waveguide radiation diagram.

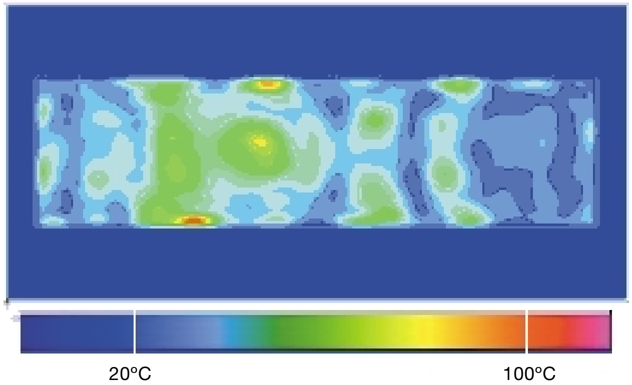

Figure 8. MAFIA simulation of the heating density obtained after 2 min of soil radiation exposure through the slotted waveguide.

In agreement with the measured temperature, the evolution of temperature with time is practically linear during heating and cooling phases at 5 cm, and the temperature variation during heating is faster than during cooling (Fig. 9). When a soil has a higher humidity, it reaches a lower temperature. This may be due to the higher heat dissipation involved in evaporation processes in surface layers.

For a given soil column, the temperature variations are different with depth. They have a low amplitude for depths equal or superior to 10 cm, and for radiation exposure times shorter than 5 min.

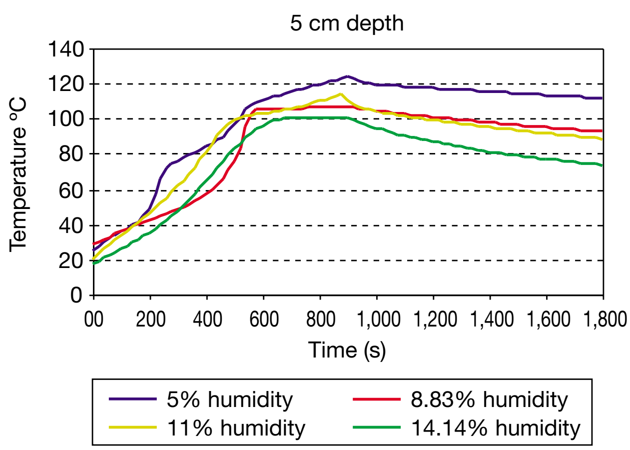

Figure 9. Temperature variation with time during a heating phase of 15 min followed by a cooling phase of 15 min for different soil humidities.

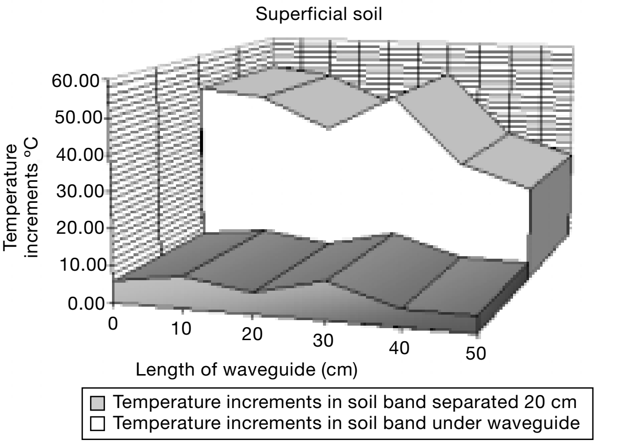

Figure 10. Profiles of temperature increment distribution along longitudinal and transversal direction to the guide in surface soil to 5 min of radiation.

Figures 10, 11 and 12 show the map of temperature increments for the surface layer and in depths of 5 and 10 cm, depicting the soil band under the waveguide and the soil band separated 20 cm from the waveguide line.

As in the MAFIA simulations, the soil temperatures reached in layers located deeper than 10 cm are very low. They are not high enough to eliminate pathogens with short radiation times.

The results allowed the power ratios absorbed by each sector to be estimated under the waveguide line as well as in the adjacent strips (Table 1).

In these experiments, the calculated energy absorbed by soil irradiated for 5 min was 1,140 kJ. This absorbed energy corresponds to a 95% efficiency for 4 kW of power.

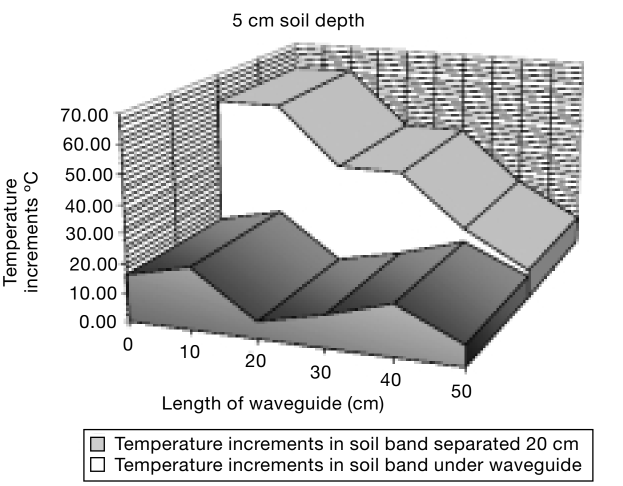

Figure 11. Profiles of temperature increment distribution along longitudinal and transversal direction to the guide in 5 cm soil depth to 5 min of radiation.

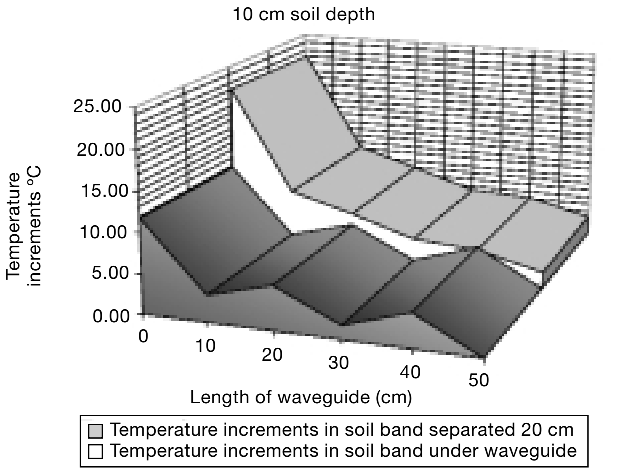

Figure 12. Profiles of temperature increment distribution along longitudinal and transversal direction to the guide in 10 cm soil depth to 5 min of radiation.

Around 74.43% of the emitted energy is absorbed by soil directly under the waveguide line and approximately 70% of this is absorbed in a strip 40 cm from the first slot. The remaining 25.57% of the energy is absorbed by the adjacent soil.

Radiation overlapping system

The thermal map obtained from the simulations is depicted in Figures 13 and 14. The distribution shown in Figure 14 corresponds to the irradiation supplied by a single emitter head of 1 kW placed in the middle of the surface. It can be seen that the radiation is concentrated in the centre of the irradiated area.

Figure 15 corresponds to soil irradiated by 4 heads placed on the middle line, 35 cm apart. The simultaneous action of several magnetrons produces a higher uniformity due to the presence of several spots at a few seconds. These hot spots increase in size when exposure time is longer and overlap when radiation exposure is longer than 1 min.

Soil temperature *versus* time for different soil humidity is depicted by Figure 15. It can be noted that the temperature increases linearly during the first 180 s and tends rapidly towards an asymptotic value between 95 and 100ºC. The asymptotic value of the temperature is higher when the soil is wetter. The power ratios in each sector, along the longitudinal and transversal directions, are presented in Table 2.

Table 1. Power absorbed (W, %) by each soil surface sector (10 × 20 cm)

Sectors	Distance to fist slot of waveguide	Power ratio absorbed by each sector		Power absorbed by each sector (W)	
		Soil under waveguide	Soil separated 20 cm to waveguide line	Soil under waveguide	Soil separated 20 cm from waveguide line
1	0	5.67%	19.38%	736.42	215.37
2	10	5.72%	16.82%	639.07	217.36
3	20	3.20%	12.47%	473.87	121.77
4	30	3.97%	13.22%	502.22	150.70
5	40	4.37%	8.05%	305.98	166.08
6	50	2.64%	4.50%	170.83	100.35
Total		25.57%	74.43%	2,828.38	971.62

In this oven, the energy absorbed by the trays exposed inside the cavity to a 3 min irradiation exposure was 693 kJ. For an effective power of 4 kW, this energy corresponds to an absorption efficiency of 96.25%. The temperature reached in this area is 90ºC for 5 min of radiation and the energy used is approximately 3.5 W cm^{-2} of treated soil. Therefore thermal depth points are reached.

Discussion

Although microwave processing of bioproducts (food and biological material in general) offers a number of well-known advantages, namely faster and more efficient heating (Nelson, 1996; Mavrogianopoulos *et al.*, 2000), there are several problems associated with its industrial usage for operations such as drying, pasteurization and sterilization due to the uneven pattern of microwave heating: unsatisfactory (non-homogeneous) quality of the final product, insufficient microbiological destruction in cold areas, and safety hazards due to over-heating (Banga *et al.,* 1999). This work studies different systems for improving the uniformity of the radiation.

Modern process engineering methods are based on mathematical modelling and simulations of microwave distribution such as MAFIA, but it is still necessary to check the results on the irradiated material (Sunberg *et al.*, 1996). Each material has its own features: dielectric properties, irradiated sample sizes, irregular surface, etc. It is, therefore, necessary to conduct specific studies and validations. This approach has been followed in this work to evaluate two irradiation systems for soil disinfestation.

The use of several magnetrons working simultaneously or waveguides have been modelled by several researchers to achieve large areas of radiation in other applications such as drying in the ceramics industry (Oktay and Akman, 1999) or drying wood (Antti, 1999). However, for practical application in soil disinfection, it is necessary to make specific ovens

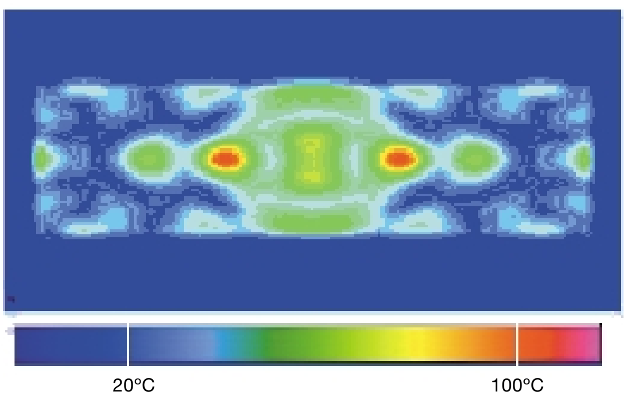

Figure 13. MAFIA simulation of heat density obtained by a single emitter head with vertical waveguide and end opening placed in middle of soil surface for 1 min of radiation exposure.

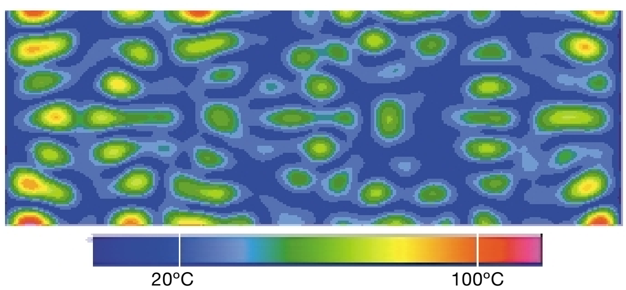

Figure 14. MAFIA simulation of heat density obtained by overlapping four emitter magnetrons for a few seconds of radiation.

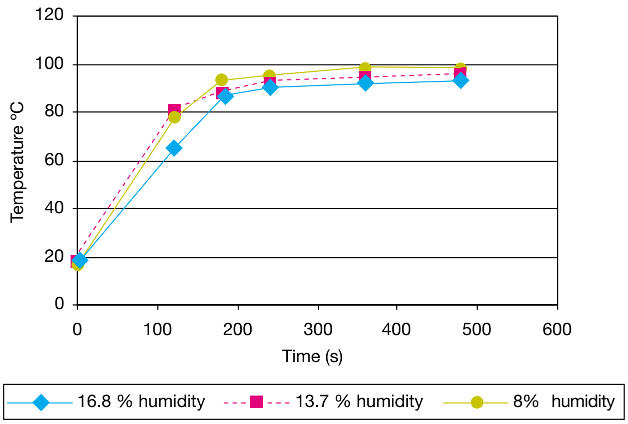

Figure 15. Soil temperature variation with the time for different humidities when the soil is irradiated by four 1 kW magnetrons working simultaneously placed in the central line.

capable of producing enough energy, with adequate uniformity, to cover larger areas. We have evaluated two systems for this purpose. In accordance with the MAFIA simulations, both of them are close to these objectives.

With respect to the slotted waveguide system evaluation, the empirical thermal maps (Fig. 10 to 12) have shown that the area where efficient disinfection would be achieved is reduced to about a fourth of the studied surface, near to the power source, because the radiation is not homogeneous. This result contrasts with the thermal distribution obtained by Cebrian-Gascón *et al.* (1999) who, working in the microwave distribution through slotted waveguides, predicted a better, and a more uniform heat distribution in the soil.

To date, many researchers have studied the effects of microwaves on different pathogens and seeds, determining death thermal points (Nelson, 1996; Morozov *et al.*, 1999; Mason, 2000; Mavrogianopoulos *et al.*, 2000), but for practical application in soil, the temperatures reached at different soil depths must be checked for large areas of radiation, as was done in this work.

On the other hand, the two evaluated prototypes reached these death points around 90ºC (Mason, 2000) in most parts of the irradiated area.

Although both radiation systems offer interesting possibilities for achieving a satisfactory level of uniformity in the distribution of radiation in agricultural soils, it is necessary to consider some recommendations.

The system based on the slotted waveguide could be improved by installing several waveguides in parallel and reverse directions. In this way, the energy can be deflected to lateral bands covering a wider area of soil.

The slow temperature decrease during the cooling phase may facilitate soil disinfection because it increases the time that microorganisms are above the critical thermal points.

Due to the hard temperature attenuation with depth (Fig. 10 to 12), soil disinfection with microwaves is more efficient in thin soil layers (< 10 cm) where lethal temperatures can be achieved within very short times.

For practical use, the prototype based on overlapping magnetrons appears to be more efficient than the waveguide prototype, because it allows lethal temperatures to be reached in a shorter time. The main reason is that the overlapping system irradiates thin soil layers of 6 cm, allowing the energy previously deflected in depth to be used in the upper soil layers. The radiation emitted simultaneously by several magnetrons produces a better uniformity of tempera-

Table 2. Power absorbed (W, %) by each soil surface sector (20 × 25 cm)

Sectors	Distance to oven gate	Power ratio absorbed by each sector		Power (W) absorbed by each sector	
		Right band	Left band	Right band	Left band
1	10	5.35%	5.98%	205.98	230.23
2	30	6.25%	6.26%	240.63	241.01
3	50	6.23%	7.12%	239.86	274.12
4	70	6.86%	6.92%	264.11	266.42
5	90	7.22%	6.81%	277.97	262.19
6	110	6.14%	7.32%	236.39	281.82
7	120	5.12%	5.98%	197.12	230.23
8	140	4.86%	5.58%	187.11	214.83
Total		48.03%	51.97%	1,849.16	2,000.85

ture, which could improve its performance when mode *shakers* are employed as in Ortigosa (1999).

Comparing both prototypes we can observe that the speed of the temperature variation is higher in the system based on several magnetrons emitting simultaneously over substratum trays than in the system based on the slotted waveguide. However, the ratio of effective energy absorbed by the soil is similar for both systems. This ratio is approximately 95%.

If the soil is wetter, the temperature reached in the deeper parts of the soil is lower (Fig. 9). On the other hand the temperature reached is higher when narrow layers are irradiated (Fig. 15). For this reason, appropriate irrigation of the soil could improve the disinfection process of substratum trays in sowing lines of plant nurseries.

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